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An Application of PEER Performance-Based Earthquake Engineering Methodology

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Overview

Performance-based earthquake engineering (PBEE) methodology is a focus of the Pacific Earthquake Engineering Research (PEER) Center. The final output of the PBEE method is a probabilistic quantitative description of the seismic performance of a structure using metrics that are of immediate use to engineers and other stakeholders. This research digest illustrates the concept of PBEE through a simplified example, where a prototype building near the University of California, Berkeley campus is designed and modeled. Suites of ground motions that represent the hazard are used in a series of nonlinear dynamic analyses to determine peak building responses. Major structural and nonstructural components are identified and separated into different performance groups (PGs). Depending on the building response, different damage states and the corresponding repair costs for all PGs are identified. Simple statistical simulation procedures are used to efficiently generate large numbers of cost realizations, making it possible to describe probabilities of repair costs exceeding threshold values.

Applicability

Application of the PBEE concept to calculate repair cost is illustrated using a typical special steel moment resisting frame building located on the University of California, Berkeley campus. Similar procedures can be used for different decision variables (e.g., casualties, downtime), seismic hazard exposure, and building systems, provided a sufficient database to assess the structural and nonstructural performance under certain peak building responses exists.

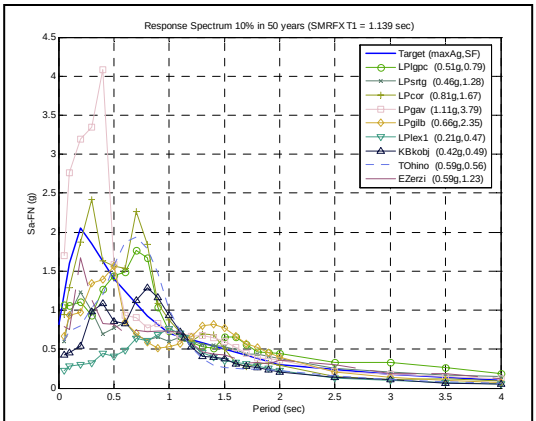

Figure 1 – Scaled response spectra

Intensity Measure

Ground motions that represent the hazard at University of California, Berkeley campus are selected from the U.C. Berkeley Seismic Guidelines [1]. For this example, ground motions are scaled to match the target spectrum at the first-mode period of the structure. Therefore, spectral acceleration at the first-mode period is the intensity measure (IM) of the ground motion. Alternative approaches to scaling ground motions and alternative

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intensity measures could be used. Figure 1 shows a sample of the scaled response spectra and the scaling factors for the ground motions used in this analysis.

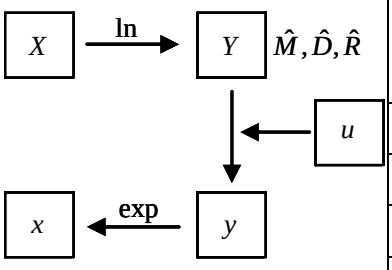
Peak Building Responses and Correlated EDP Generator

With the selected ground motions, a series of nonlinear dynamic analyses are used to determine engineering demand parameters (EDPs). In this study, Open System for Earthquake Engineering Simulation (OpenSees) software is used for the analyses [2]. However, any structural analysis program capable of representing the nonlinear dynamic response of the building can be used. From the results of the nonlinear dynamic analysis, peak structural responses are identified and summarized in an EDP matrix (Table 1 shows a sample). Because each row of the EDP matrix is calculated from a single ground motion, the correlation among EDPs is preserved. The EDP matrix can be extended by considering any number of EDPs and any number of ground motions.

Table 1 – Correlated EDP matrix

10%/50yrs	Δu_{1max} (%)	Δu_{2max} (%)	Δu_{3max} (%)	a_{gmax} (g)	a_{2max} (g)	a_{3max} (g)	a_{Rmax} (g)
GM 1	1.26	1.45	1.71	0.54	0.87	0.88	0.65
GM 2	1.41	2.05	2.43	0.55	0.87	0.77	0.78
GM 3	1.37	1.96	2.63	0.75	1.04	0.89	0.81
GM 4	0.97	1.87	2.74	0.55	0.92	1.12	0.75
GM 5	0.94	1.80	2.02	0.40	0.77	0.74	0.64
GM 6	1.73	2.55	2.46	0.45	0.57	0.45	0.59
GM 7	1.05	2.15	2.26	0.38	0.59	0.49	0.52
GM 8	1.40	1.67	2.10	0.73	1.50	1.34	0.83
GM 9	1.59	1.76	2.01	0.59	0.94	0.81	0.72
GM 10	0.83	1.68	2.25	0.53	1.00	0.90	0.74

Instead of running additional nonlinear dynamic analyses to obtain more EDP realizations, a joint lognormal distribution is fitted to the EDP matrix. Additional correlated EDP vectors are generated using the correlation matrix and artificially generated standard normal random



Definitions: X = EDP data for a given IM level (assume joint lognormal distribution); $Y = \ln(X)$; $\hat{M}, \hat{D}, \hat{R}$ = sample statistics of Y (as shown in Equations 1 through 4); u = generated standard normal random variable; y = simulated ln(EDP data); x = simulated EDP data.

Mean vector:	$\hat{M} = mean(Y)^T$	Equation 1
Standard Deviation Matrix:	$\hat{D} = diag(std(Y))$	Equation 2
Correlation Coefficient Matrix:	$\hat{R} = corrcoef(Y)$	Equation 3
Cholesky Factorization of correlation coefficient matrix:	$L = chol(\hat{R})^T$	Equation 4
ln(EDP) vector:	$y = \hat{D} * L * u + \hat{M}$	Equation 5

Figure 2 – Correlated EDP generator

variables (u). This process preserves the statistical correlation among the EDPs and eliminates the time-consuming nonlinear response history analyses. Figure 2 shows the process of obtaining additional correlated EDP vectors.

Performance Groups and Damage Model

In the methodology adopted here, the simulation procedure described previously is used to generate a single realization of EDPs, then damage associated with that EDP realization is calculated. The process is repeated a large number of times to obtain a representative sample of damage states. To facilitate the calculation, major components in the building are organized into performance groups. In this example, different performance groups were defined for each story and, within each story, for drift sensitive structural components, for drift-sensitive nonstructural components and contents, and for acceleration-sensitive nonstructural components and contents. For each performance group, damage states are defined that are meaningful in relation to repair actions (e.g., fracture of beam-column connection weld). For each damage state, a damage model (fragility relation) defines the probability of damage being equal to or greater than the threshold damage given an EDP, as shown in Figure 3a. Depending on the EDP values, the probabilities of the performance group being in each damage state can be computed. A uniformly distributed random number generator is used to select the performance group damage state.

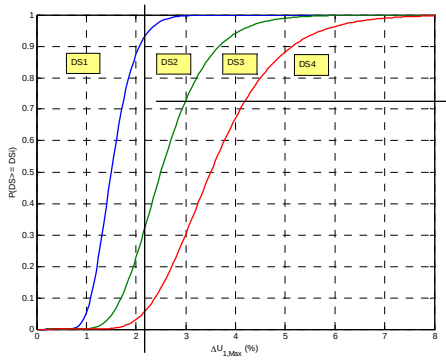


Figure 3a – PG fragility curves

	PG1 - SH12				PG2 - SH23				PG3 - SH3R			
	DS1	DS2	DS3	DS4	DS1	DS2	DS3	DS4	DS1	DS2	DS3	DS4
Finish_protection	0	6000	6000	6000	0	6000	6000	6000	0	6000	6000	6000
Ceiling_system_removal	0	2000	3000	5000	0	3000	3000	5000	0	3000	3000	5000
Drywall_assembly_removal	0	800	800	6000	0	800	800	6000	0	800	800	6000
Miscellaneous_MEP	0	2	4	6	0	2	4	6	0	2	4	6
Remove_exterior_skin	0	0	0	5600	0	0	0	4000	0	0	0	3000
Welding_protection	0	1500	1500	1500	0	1500	1500	1500	0	1500	1500	1500
Shore_beams_below_remove	0	0	0	12	0	0	0	12	0	0	0	12
Remove_replace_connection	0	0	0	3000	0	0	0	3000	0	0	0	2000
Replace_slab	0	70	70	1600	0	70	70	1600	0	70	70	1600
Miscellaneous_MEP_and_cleanup	0	2	4	6	0	2	4	6	0	2	4	6
Wall_framing(studs_drywall_tape_paint)	0	800	800	6000	0	800	800	6000	0	800	800	6000
Replace_exterior_skin(from_salvage)	0	0	0	5600	0	0	0	5600	0	0	0	5600
Ceiling_system	0	2000	3000	5000	0	3000	3000	5000	0	3000	3000	5000

Figure 3b – Repair quantities for performance groups

Loss Computation

Once the damage states of all the performance groups for the building are determined for a given EDP realization, the quantities of required repair materials are taken from a lookup table (example shown in Figure 3b). The total repair material quantities for the building are summed over all performance groups. For this simplified example, the performance groups are assumed to be statistically independent. The total structure repair cost is computed by multiplying the total repair material quantities by the unit price obtained from a look-up table, summed over all materials. This is the repair cost for one realization of EDPs. The process is repeated a large number of times to obtain a distribution of costs given the hazard level represented by the IM. (In this example, a tri-linear cost function represented the relation between unit cost and quantity; a simple improvement in this procedure would incorporate cost uncertainty.)

Figure 4 shows the fitted lognormal distribution of the building repair cost for four different IM levels. Curves such as these can be used to quantify the annual frequency of the total repair cost exceeding a given threshold as follows: the complement of each CDF (cumulative distribution function) curve presented in Figure 4 is multiplied by the slope of the hazard curve at the corresponding IM level; the resulting curves are integrated across IM levels. Figure 5 shows the annual rate of exceeding various total repair cost thresholds for all the IM levels. Furthermore, the mean cumulative annual total repair cost can be obtained by integrating the loss curve shown in Figure 5 along the range of repair cost thresholds.

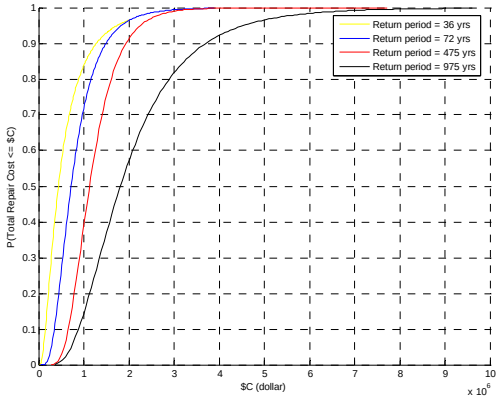


Figure 4 – CDF for P(TC<=$C|IM)

Summary

With the procedures presented, the PBEE methodology can be used to develop various expressions of repair costs. For example: 1) expected repair cost for a M7 earthquake scenario; 2) 90% probability that repair cost does not exceed a given threshold for a 975-yr return period hazard level; 3) mean cumulative annual total repair cost; 4) deaggregation of the total repair cost to help inform design decisions. The procedure can also be used as a tool to compare performance of different structural systems.

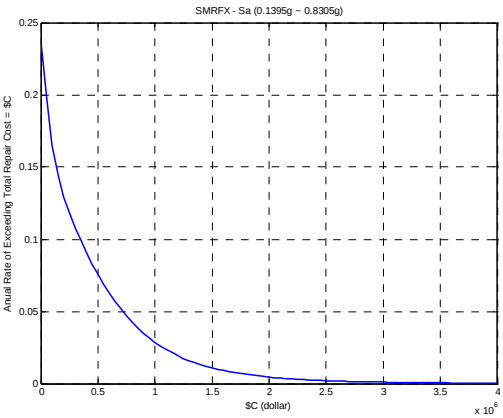


Figure 5 – Loss curve

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References

1. *University of California, Berkeley, Seismic Guidelines*, 2003.
2. *Open System for Earthquake Engineering Simulation (OpenSees)*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, http://opensees.berkeley.edu/

Keywords

Performance Based Earthquake Engineering (PBEE), Intensity Measures (IM), Engineering Demand Parameters (EDP), Fragility curves, Damage Measure (DM), repair costs, mean annual cost, loss curves.